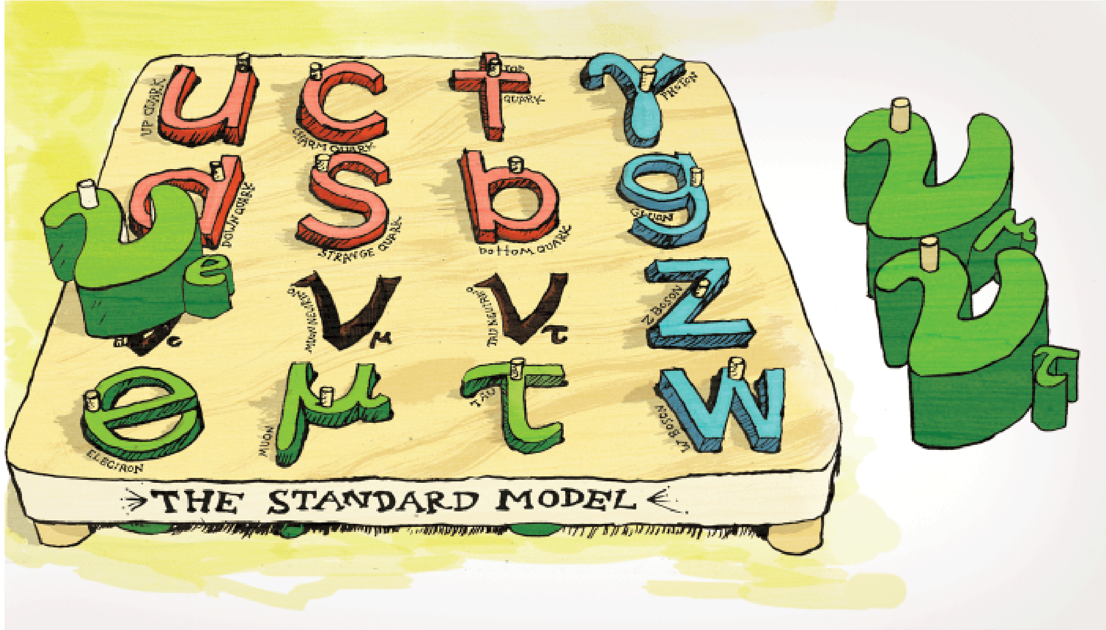
What Can We Learn in the Next 10 Years?



André de Gouvêa – Northwestern University

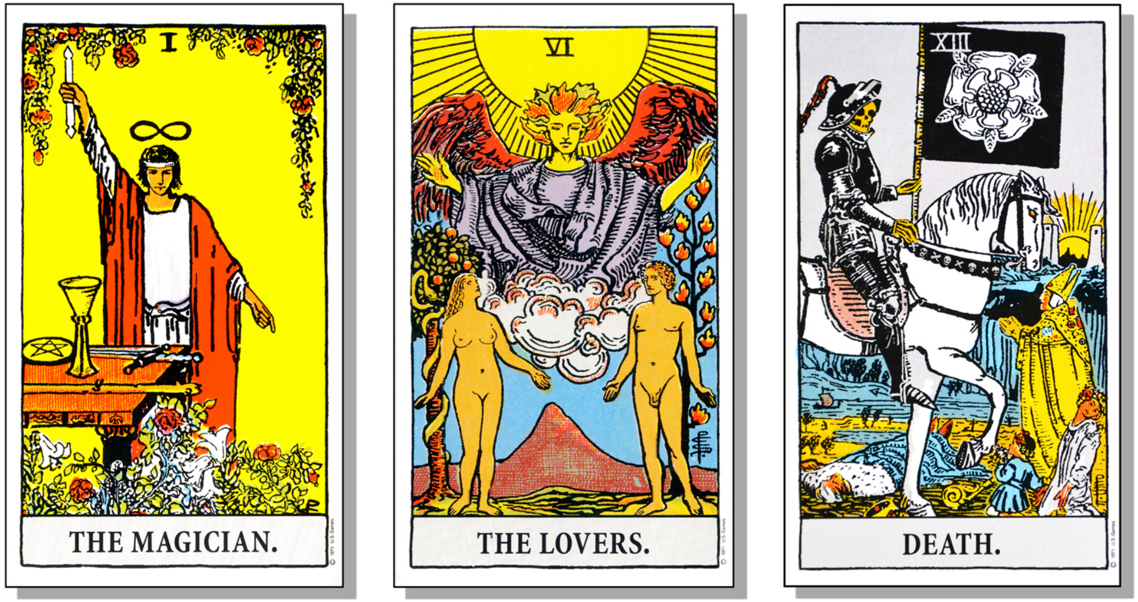
***W**orkshop on the **I**ntermediate **N**eutrino **P**rogram – BNL*

February 4–6, 2015

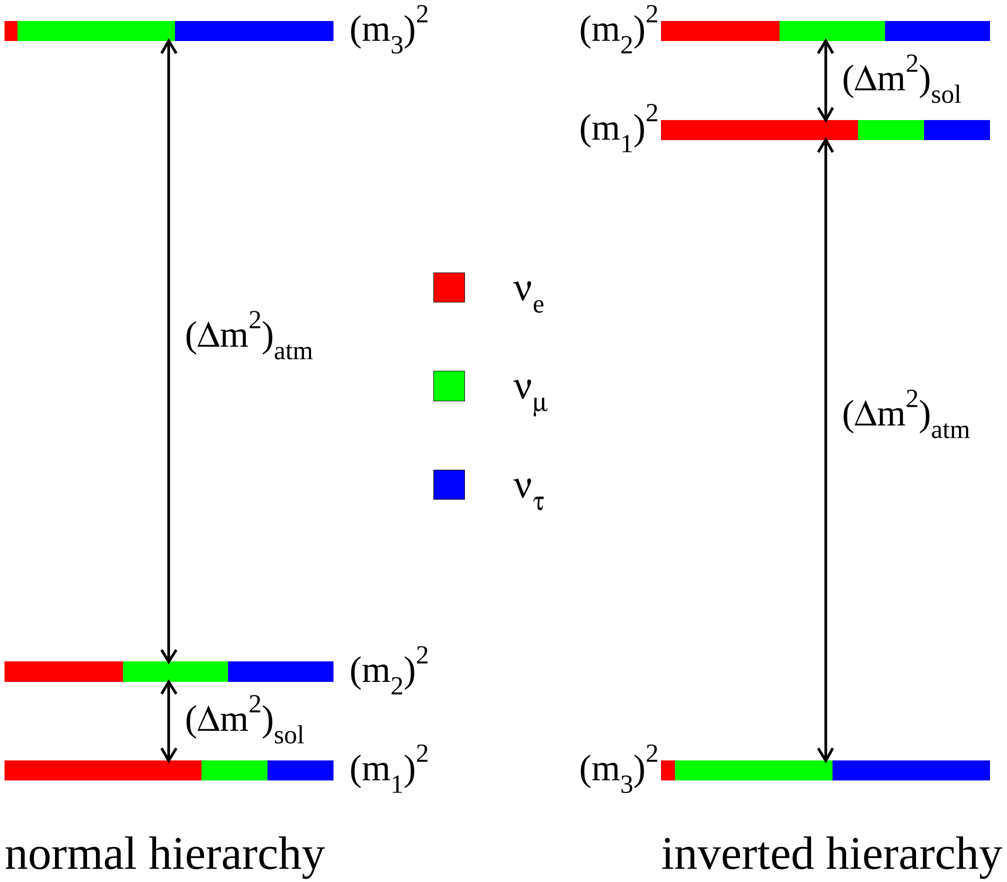
Disclaimer: CAN $\neq$ WILL

"Alas, it is always dangerous to prophesy, particularly, as the Danish proverb says, about the future."

Journal of the Royal Statistical Society: Series A (General), Proceedings of the Meeting, [Speaker: Bradford Hill], Page 147, Volume 119, Number 2, 1956, Blackwell Publishing for the Royal Statistical Society.



What We Know We Don't Know: Missing Oscillation Parameters

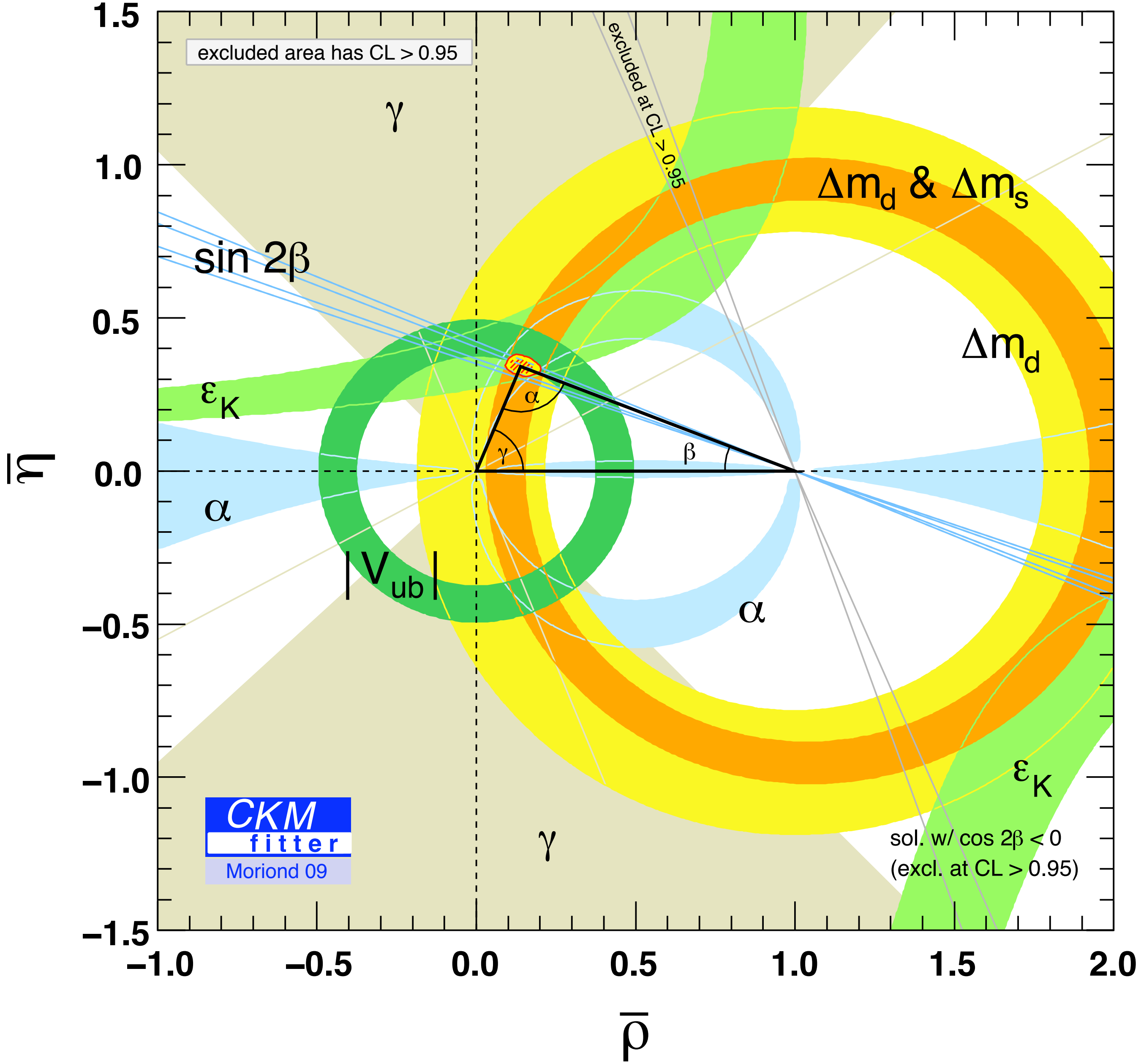


- ~~What is the ν_e component of ν_3?~~ $(\theta_{13} \neq 0!)$
- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$
- Is ν_3 mostly ν_μ or ν_τ? $(\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?)$
- What is the neutrino mass hierarchy? $(\Delta m^2_{13} > 0?)$

$\Rightarrow$ All of the above can "only" be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

What we ultimately want to achieve:



We need to do <u>this</u> in the lepton sector!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu 2}|^2 + |U_{\tau 2}|^2$ – solar data;
- $|U_{e2}|^2 |U_{e1}|^2$ – KamLAND;
- $|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2 (1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2 |U_{\mu 3}|^2$ (upper bound $\rightarrow$ evidence) – MINOS, T2K.

We still have a ways to go!

Long-Baseline Experiments, Present and Future (Not Exhaustive!)

- [NOW] T2K (Japan), NOνA (USA) – $\nu_\mu \to \nu_e$ appearance, ν_μ disappearance – precision measurements of "atmospheric parameters" $(\Delta m^2_{13}, \sin^2\theta_{23})$. Pursue mass hierarchy via matter effects. Nontrivial tests of paradigm. First step towards CP-invariance violation.

- [2020] JUNO (China) – $\bar{\nu}_e$ disappearance – precision measurements of "solar parameters" $(\Delta m^2_{12}, \sin^2\theta_{12})$. Pursue the mass hierarchy via precision oscillations..

- [2025] PINGU (South Pole) and INO (India)– atmospheric neutrinos – pursue mass hierarchy via matter effects.

- [2025] HyperK (Japan), LBNF (USA) – Second (real opportunity for discovery!) step towards CP-invariance violation. More nontrivial tests of the paradigm. Ultimate "super-beam" experiments.

- [>2030?] Neutrino Factories (?) – Ultimate neutrino oscillation experiment. Test paradigm, precision measurements, solidify CP-violation discovery or improve sensitivity significantly.

What Can We Learn ...? – Long-Baseline Oscillations

[see Mark Thomson's talk, next]

- Mass Hierarchy. Not guaranteed, but there is a fair chance.
- More precise measurement of θ_{23}, including potential octant information, $\sin^2\theta_{23} > 0.5$ or $\sin^2\theta_{23} < 0.5$.
- A Hint of δ.
- Multiple measurements of θ_{13}, including $|U_{e3}|^2$, $|U_{e3}U_{\mu 3}|$.
- Significant matter effects in a beam experiment.
- Precision measurement of Δm^2_{12} and $\sin^2\theta_{12}$ from JUNO. Note that the current best measurement of $\sin^2\theta_{12}$ is from solar data.

The Short Baseline Anomalies

Different data sets, sensitive to L/E values small enough that the known oscillation frequencies do not have "time" to operate, point to unexpected neutrino behavior. These include

- $\nu_\mu \to \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \to \nu_{\rm other}$ disappearance — radioactive sources;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ disappearance — reactor experiments.

None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here...

What is Going on Here?

- Are these "anomalies" related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

Need new clever experiments, of the short-baseline type!

Observable wish list:

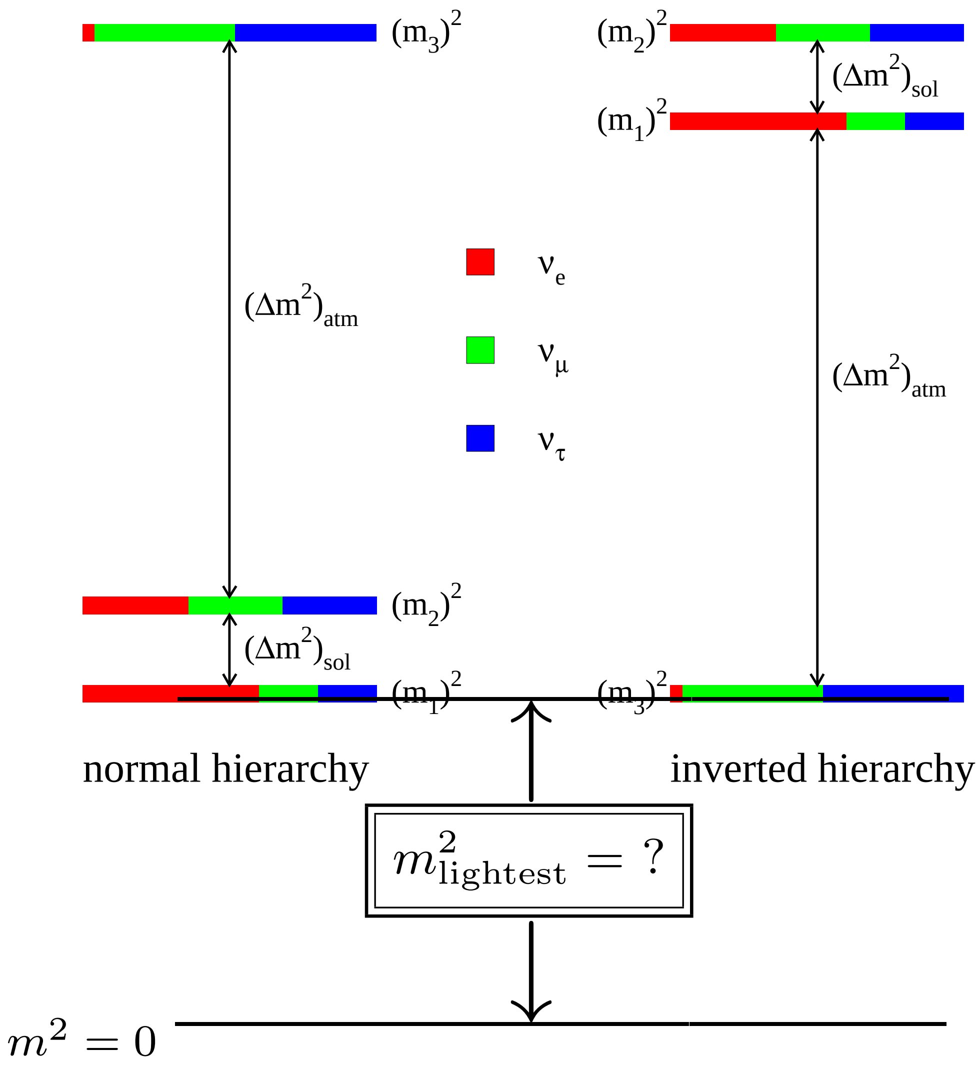
- ν_μ disappearance (and antineutrino);
- ν_e disappearance (and antineutrino);
- $\nu_\mu \leftrightarrow \nu_e$ appearance;
- $\nu_{\mu,e} \rightarrow \nu_\tau$ appearance.

What Can We Learn. . . ? – Short-Baseline Anomalies

[see Mark Thomson's talk, next]

- There are new neutrino states! [Maybe]
- There is something else going on that is new and exciting! [Maybe]
- The neutrino-oscillation interpretation to the Short-Baseline Anomalies is ruled out. [Maybe]
- We will learn a lot about neutrino detectors, neutrino beams, neutrino interactions, and how to measure small effects in the neutrino sector. Very useful!

What We Know We Don't Know: How Light is the Lightest Neutrino?



So far, we've only been able to measure neutrino mass-squared differences.

The lightest neutrino mass is only poorly constrained: $m^2_{\rm lightest} < 1$ eV^2

qualitatively different scenarios allowed:

- $m^2_{\rm lightest} \equiv 0$;
- $m^2_{\rm lightest} \ll \Delta m^2_{12,13}$;
- $m^2_{\rm lightest} \gg \Delta m^2_{12,13}$.

Need information outside of neutrino oscillations:

$\rightarrow$ cosmology, β-decay, $0\nu\beta\beta$

Big Bang Neutrinos are Warm Dark Matter

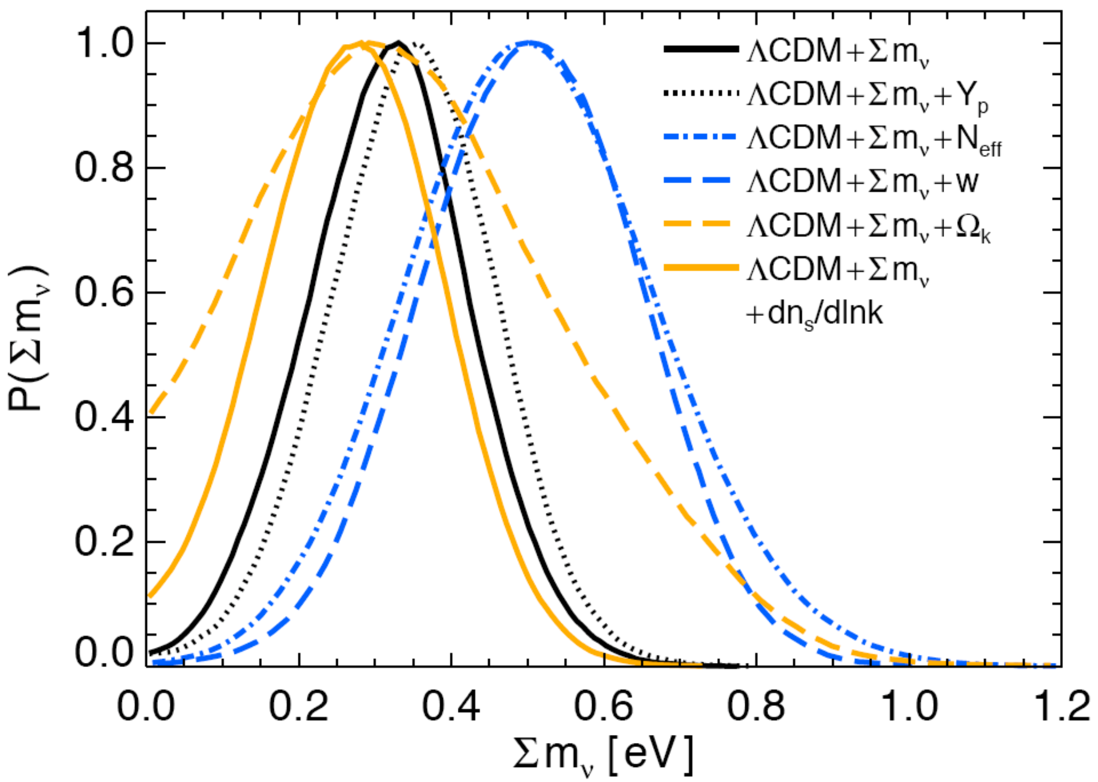


FIG. 10.— This figure illustrates the robustness of the neutrino mass detection to other parameter extensions. The marginalized one-dimensional posteriors for $\sum m_\nu$ are shown for two-parameter extensions to ΛCDM for the combined CMB+BAO+H_0+SPT$_{\rm CL}$ data sets (for w, SNe are used instead of H_0). Allowing significant curvature or running can significantly reduce the preference for nonzero neutrino masses (to 1.7 and 2.4σ respectively). Other extensions increase the preference for positive neutrino masses.

[Z. Hou *et al.* arXiv:1212.6267]

- Constrained by the Large Scale Structure of the Universe.

Constraints depend on

- Data set analysed;
- "Bias" on other parameters;
- . . .

Bounds can be evaded with non-standard cosmology. Will we learn about neutrinos from cosmology or about cosmology from neutrinos?

What Can We Learn. . . ? – Cosmology

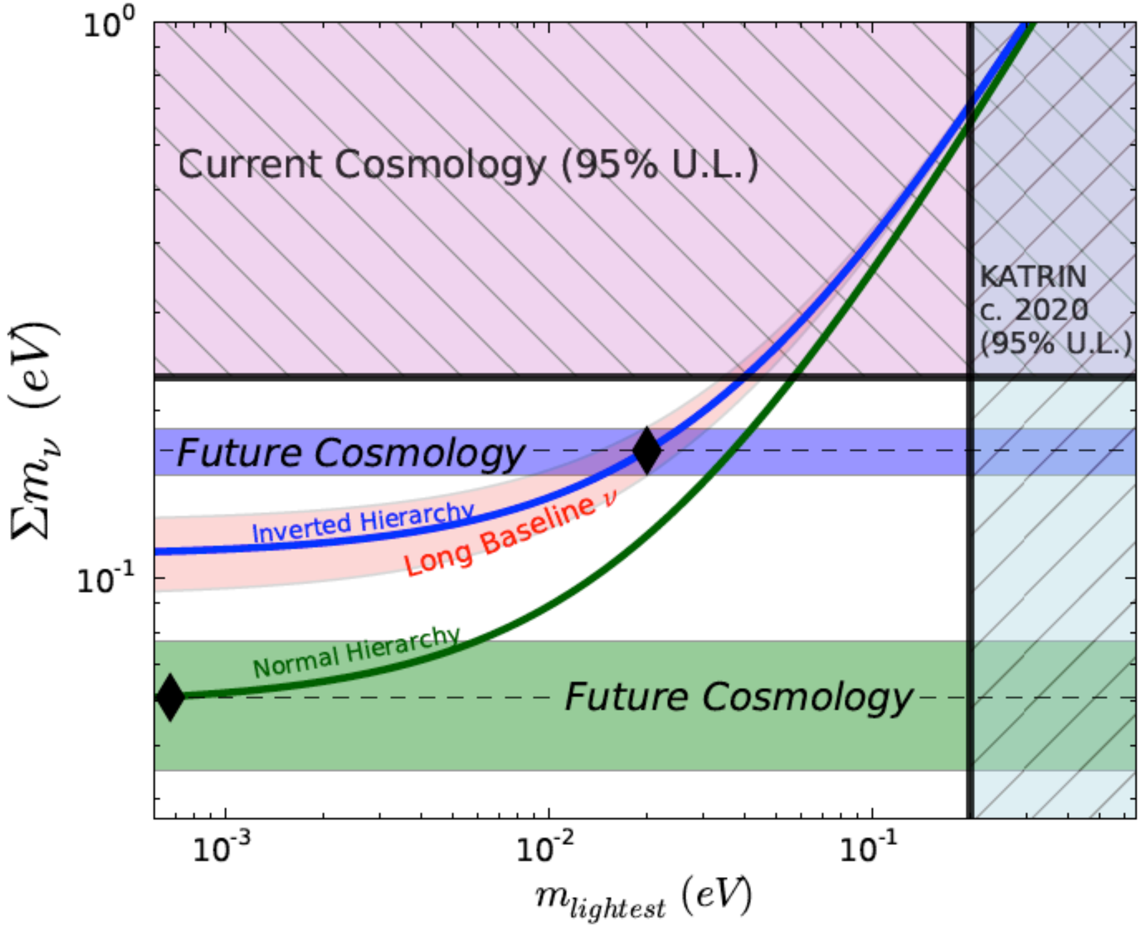


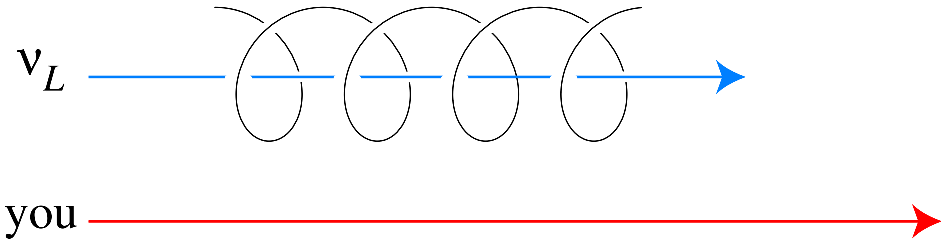
Figure 7. *Current constraints and forecast sensitivity of cosmology to the sum of neutrino masses. In the case of an "inverted hierarchy," with an example case marked as a diamond in the upper curve, future combined cosmological constraints would have a very high-significance detection, with 1-σ error shown as a blue band. In the case of a normal neutrino mass hierarchy with an example case marked as diamond on the lower curve, future cosmology would still detect the lowest $\sum m_\nu$ at greater than 3-σ.*

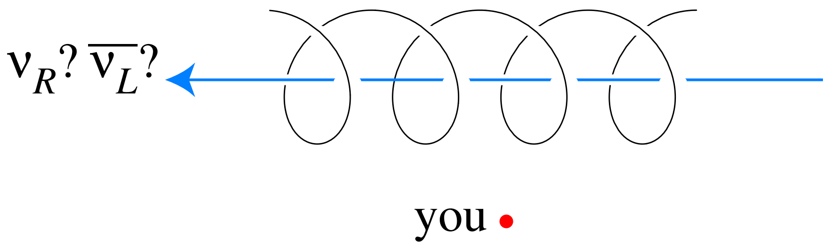
[K. Abazajian *et al.* arXiv:1309.5386]

What Can We Learn. . . ? – β-Decay

- Katrin will probe m_{ν_e} values larger than 0.2 eV. Life will be very exciting if they see a signal (see current Cosmology bounds)
- We will lean if it is possible to improve on Katrin – Project 8, Ptolemy.

What We Know We Don't Know: Are Neutrinos Majorana Fermions?





A massive charged fermion (s=1/2) is described by 4 degrees of freedom:

$$(e^-_L \leftarrow \text{CPT} \rightarrow e^+_R)$$
$$\updownarrow \text{“Lorentz”}$$
$$(e^-_R \leftarrow \text{CPT} \rightarrow e^+_L)$$

A massive neutral fermion (s=1/2) is described by 4 or 2 degrees of freedom:

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\updownarrow \text{“Lorentz”} \qquad \text{‘DIRAC’}$$
$$(\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L)$$

‘MAJORANA’

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\updownarrow \text{“Lorentz”}$$
$$(\bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L)$$

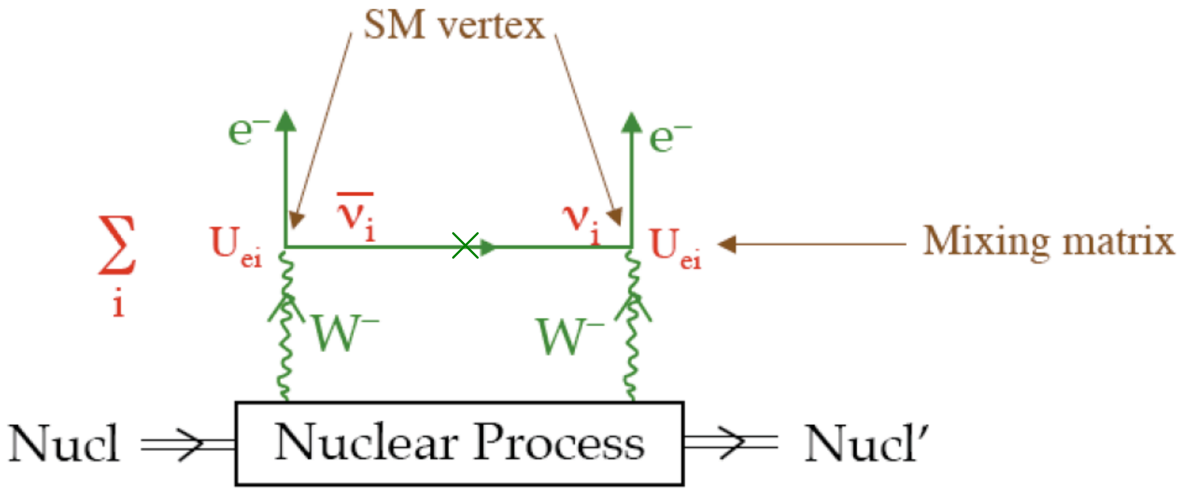
How many degrees of freedom are required to describe massive neutrinos?

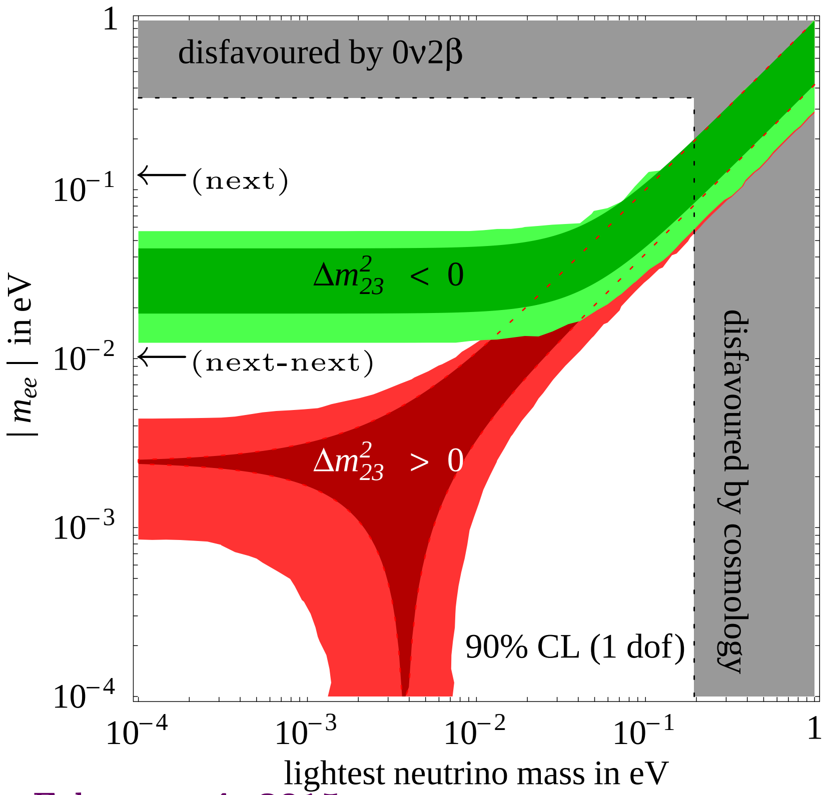
Search for the Violation of Lepton Number (or $B - L$)

Best Bet: search for

Neutrinoless Double-Beta

Decay: $\boxed{Z \to (Z+2)e^- e^-}$

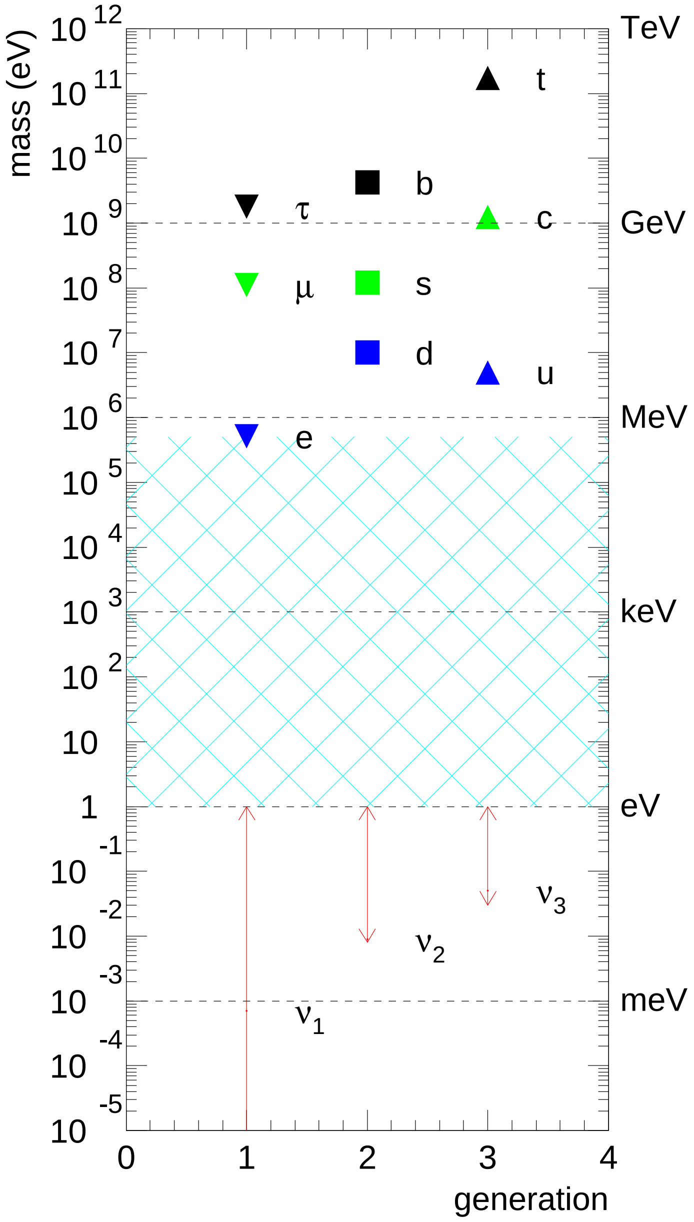




Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$

$\Leftarrow$ **clear benchmarks for next-gen. expts.**



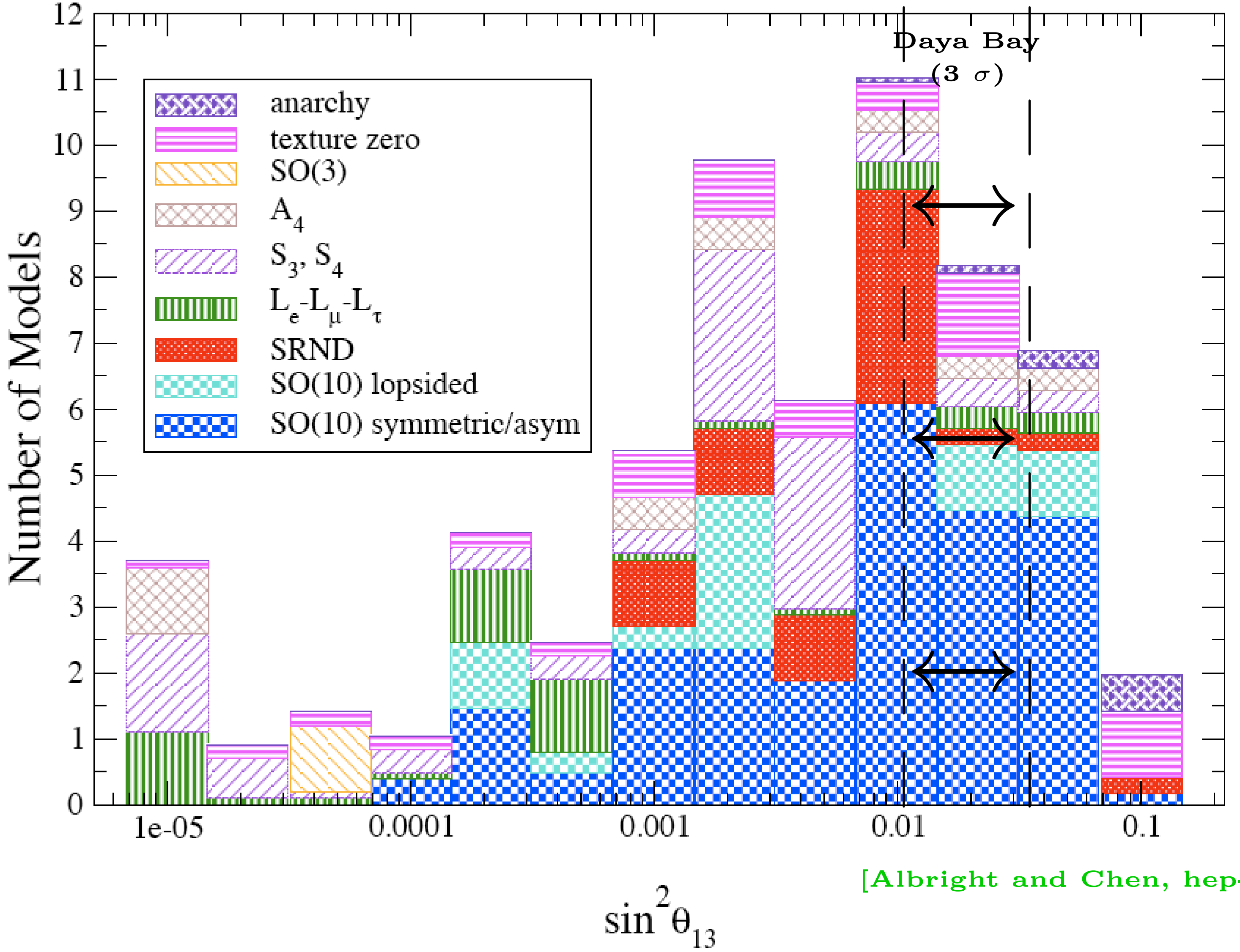
What We Are Trying To Understand:

⇐ **NEUTRINOS HAVE TINY MASSES**

⇓ **LEPTON MIXING IS "WEIRD"** ⇓

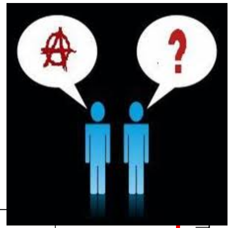
$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

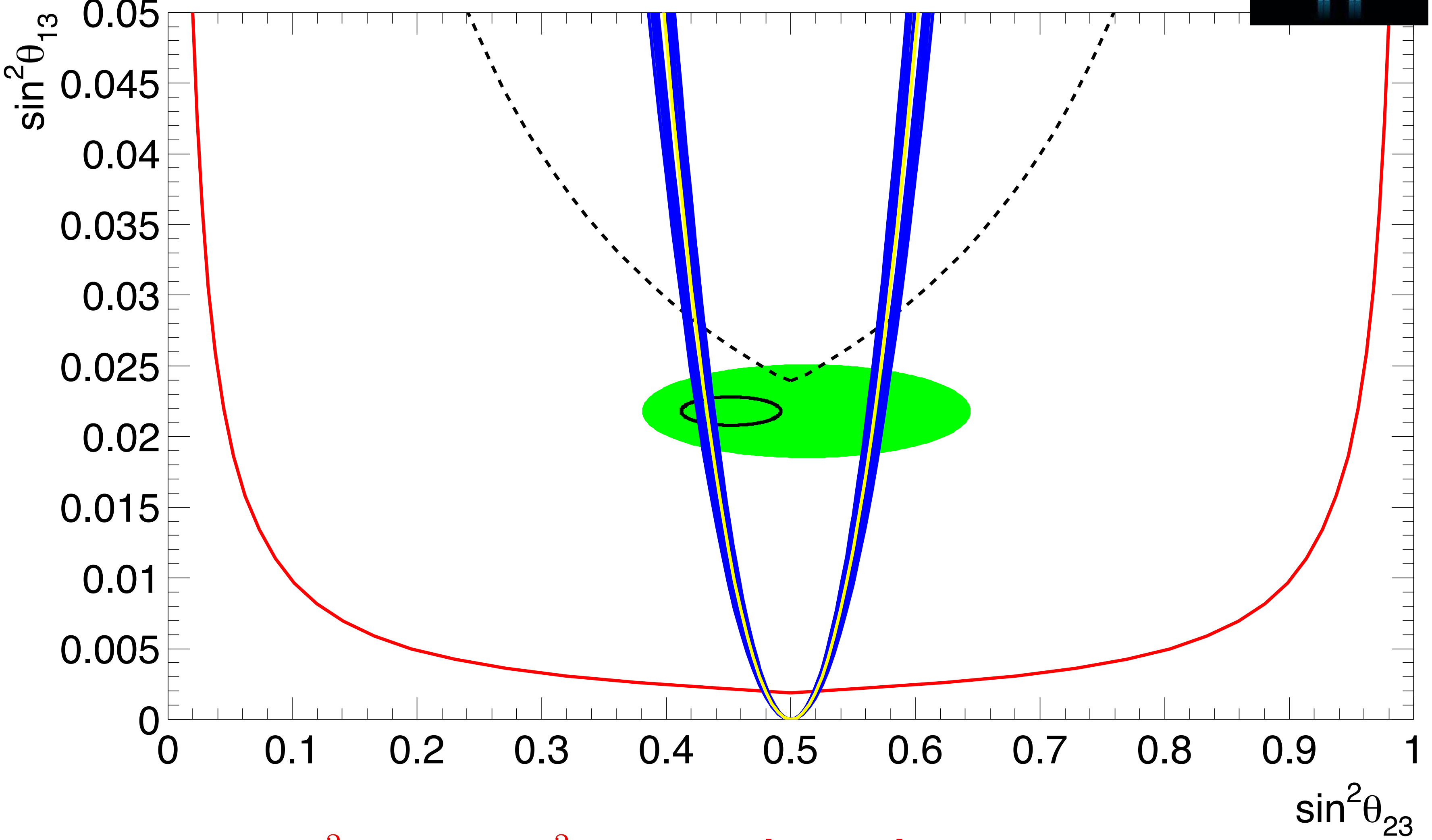


[Albright and Chen, hep-ph/0608137]

"Left-Over" Predictions: δ, mass-hierarchy, $\cos 2\theta_{23}$



Anarchy vs. Order — more precision required!



Order: $\sin^2\theta_{13} = C\cos^2 2\theta_{23},\ C \in [0.8, 1.2]$

[AdG, Murayama, 1204.1249]

What is the New Standard Model? [νSM]

The short answer is – WE DON'T KNOW. Not enough available info!

$$\Updownarrow$$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

Neutrino Masses, EWSB, and a New Mass Scale of Nature

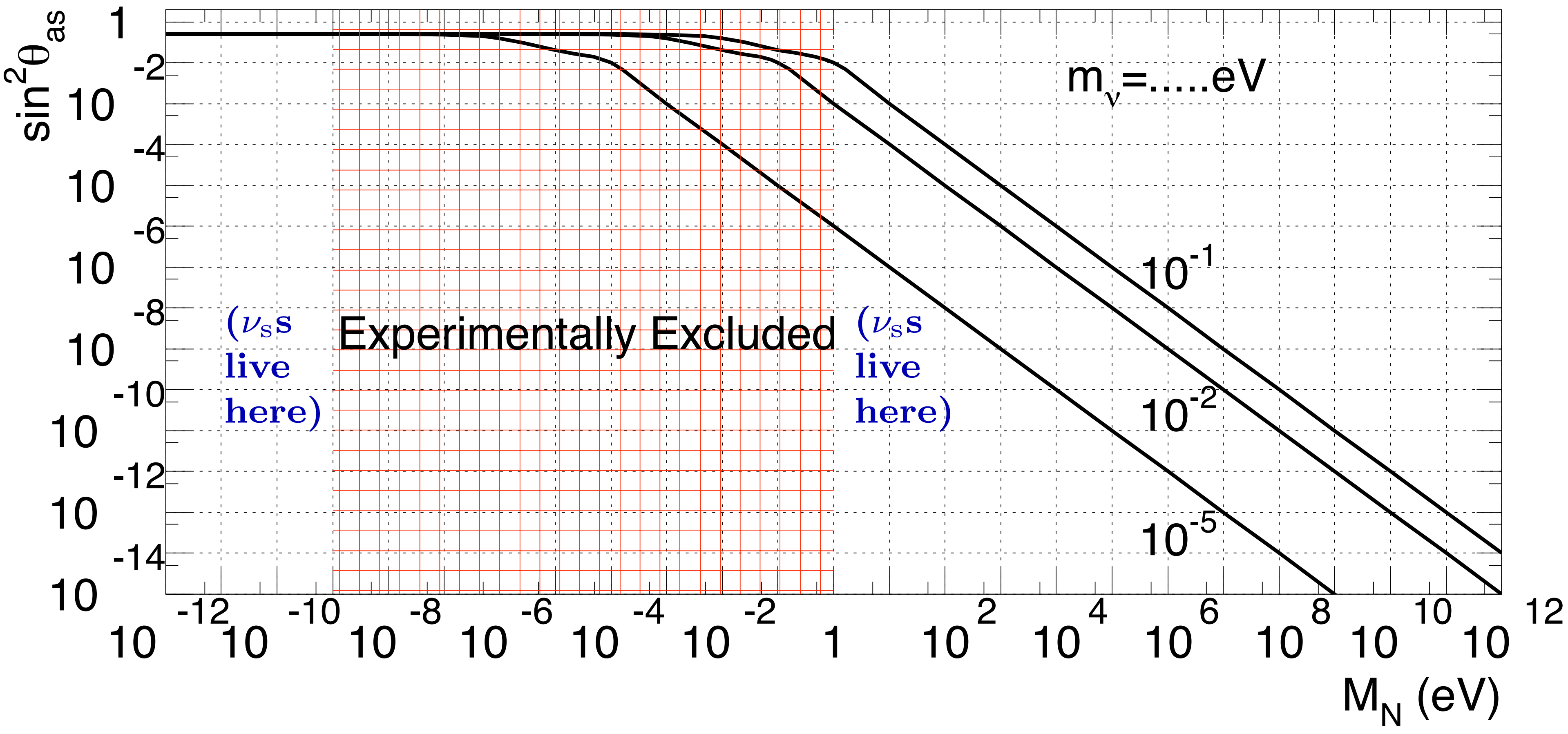
The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC, charged-lepton flavor violation, *et al* may provide more information.

Constraining the Seesaw Lagrangian

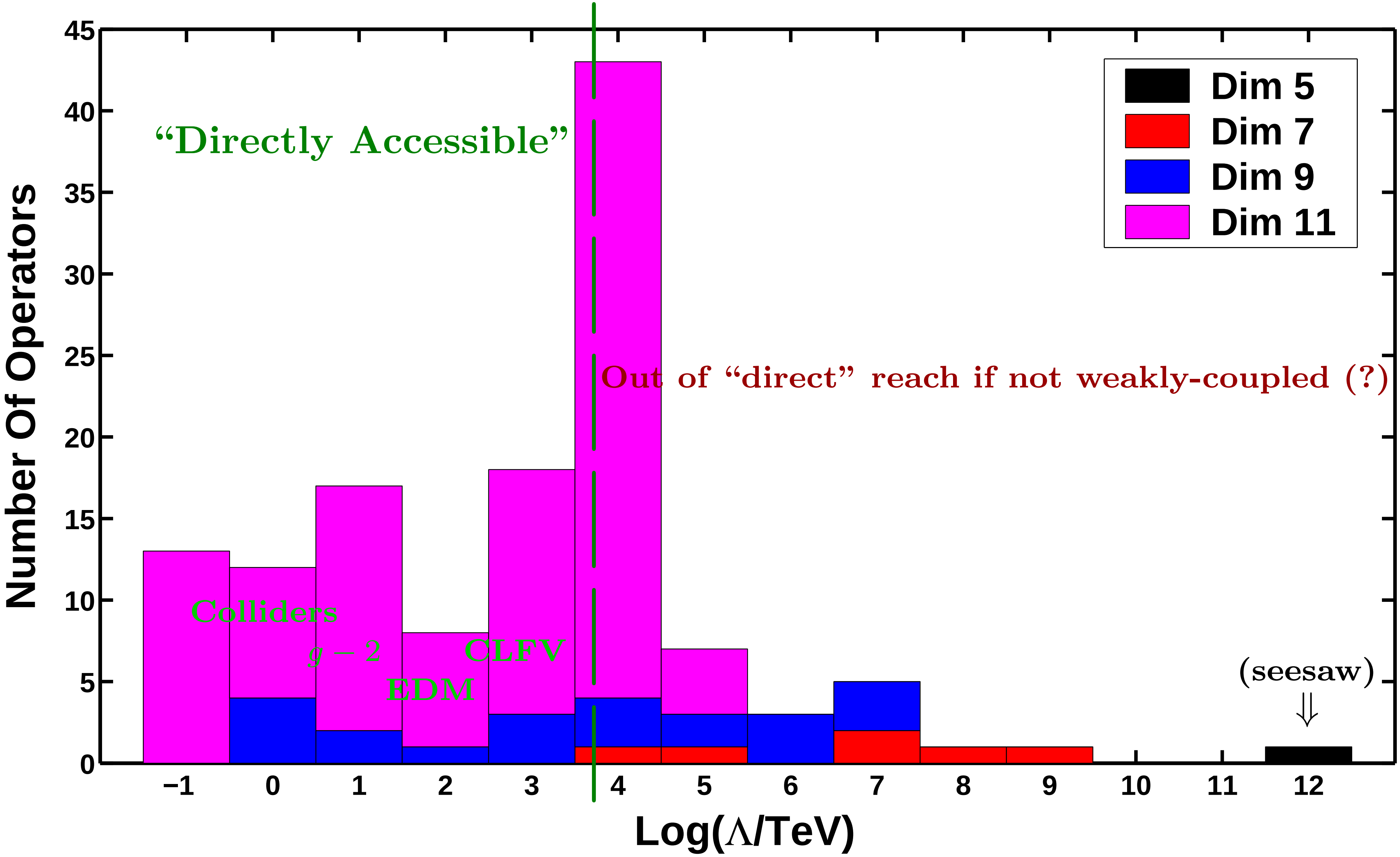


[AdG, Huang, Jenkins, arXiv:0906.1611]

Making Predictions, for an inverted mass hierarchy, $m_4 = 1$ eV($\ll m_5$)

[AdG, Huang arXiv:1110.6122]

- ν_e disappearance with an associated effective mixing angle $\sin^2 2\vartheta_{ee} > 0.02$. An interesting new proposal to closely expose the Daya Bay detectors to a strong β-emitting source would be sensitive to $\sin^2 2\vartheta_{ee} > 0.04$;
- ν_μ disappearance with an associated effective mixing angle $\sin^2 2\vartheta_{\mu\mu} > 0.07$, very close to the most recent MINOS lower bound;
- $\nu_\mu \leftrightarrow \nu_e$ transitions with an associated effective mixing angle $\sin^2 \vartheta_{e\mu} > 0.0004$;
- $\nu_\mu \leftrightarrow \nu_\tau$ transitions with an associated effective mixing angle $\sin^2 \vartheta_{\mu\tau} > 0.001$. A $\nu_\mu \to \nu_\tau$ appearance search sensitive to probabilities larger than 0.1% for a mass-squared difference of 1 eV^2 would definitively rule out $m_4 = 1$ eV if the neutrino mass hierarchy is inverted.



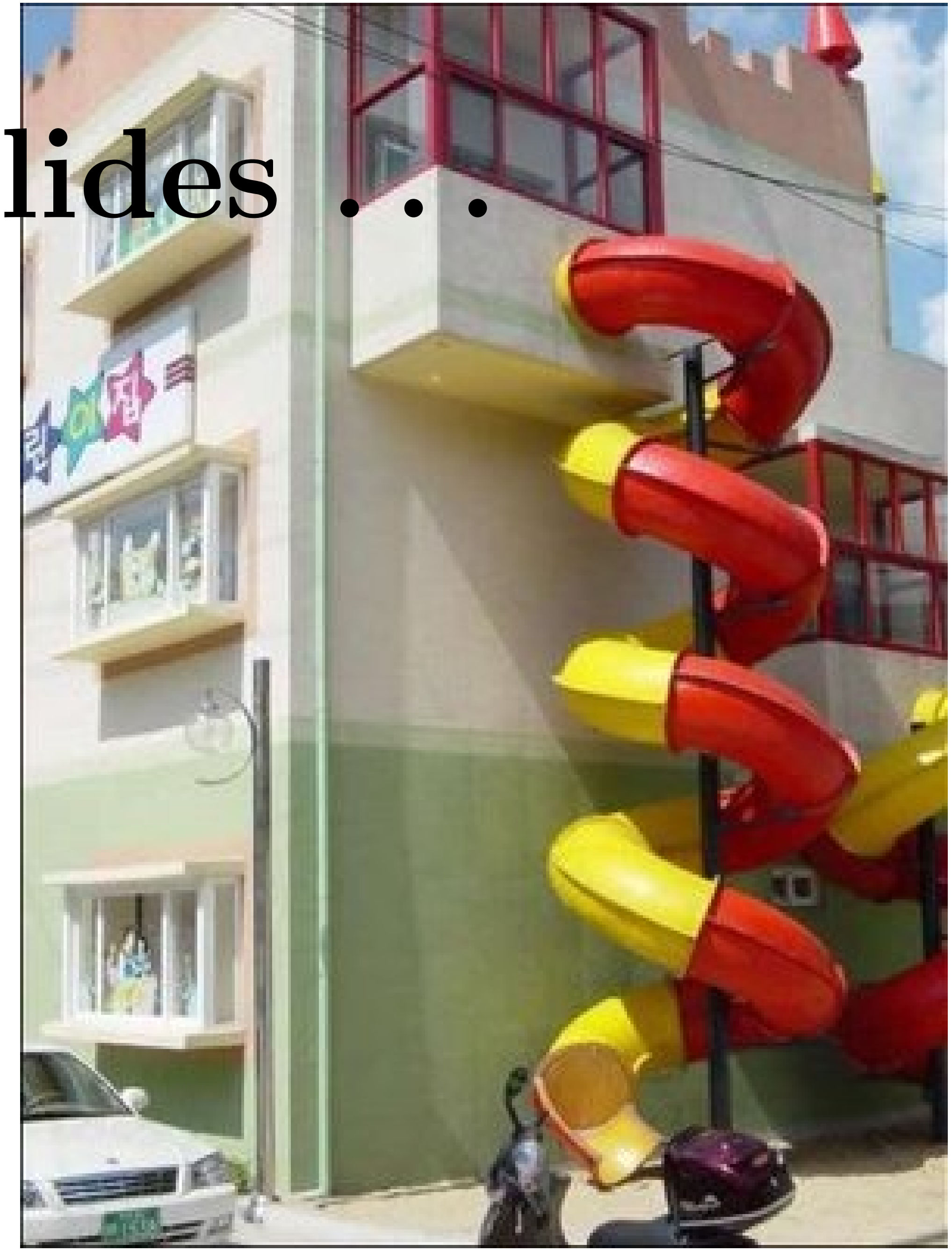
45
40
35
30
25
20
15
10
5
0
Number Of Operators
−1
0
1
2
3
4
5
6
7
8
9
10
11
12
Log(Λ/TeV)
Dim 5
Dim 7
Dim 9
Dim 11
"Directly Accessible"
Out of "direct" reach if not weakly-coupled (?)
Colliders
$g-2$
EDM
CLFV
(seesaw)
⇓

Piecing the Neutrino Mass Puzzle

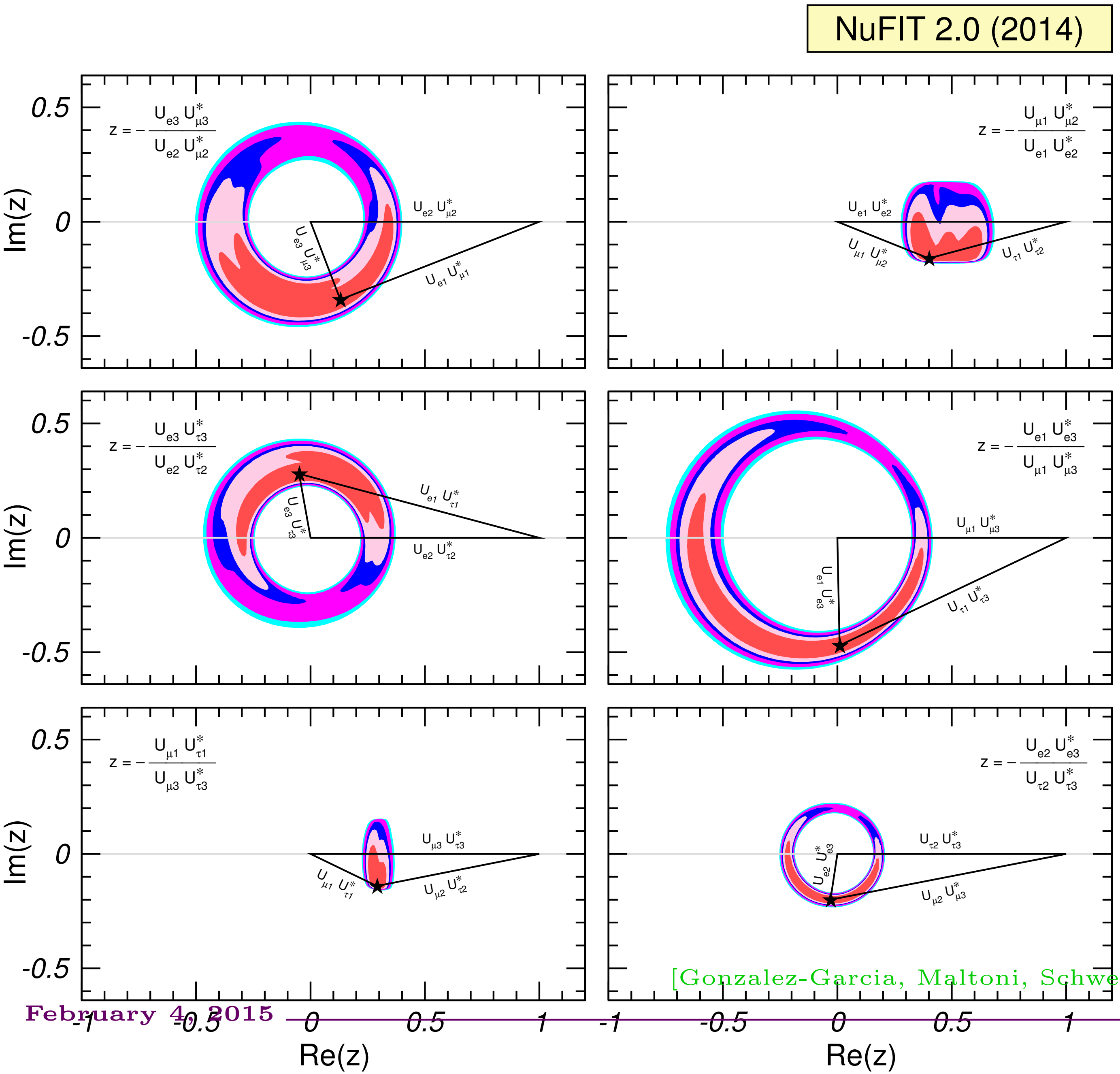
Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts, including ...

- understanding the fate of lepton-number. Neutrinoless double beta decay!
- a comprehensive neutrino oscillation program, towards "precision" oscillation physics.
- other probes of neutrino properties, including neutrino scattering.
- precision studies of charged-lepton properties ($g-2$, edm), and searches for rare processes ($\mu \to e$-conversion the best bet at the moment).
- collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- cosmic surveys. Neutrino properties affect, in a significant way, the history of the universe. Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?
- searches for baryon-number violating processes.

Backup Slides . . .



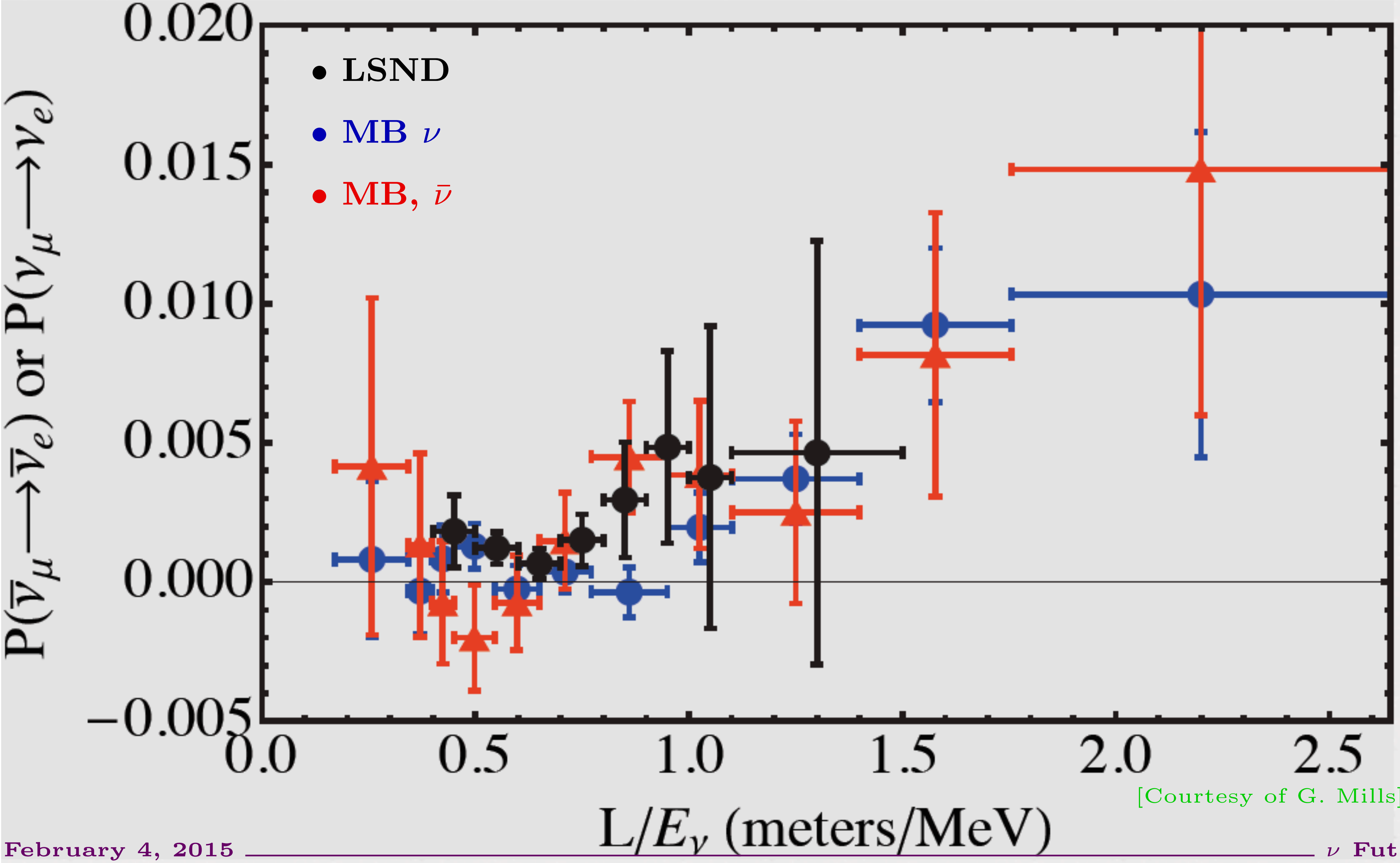
Where We Are (?) [This is Not a Proper Comparison!]



But it is a start...

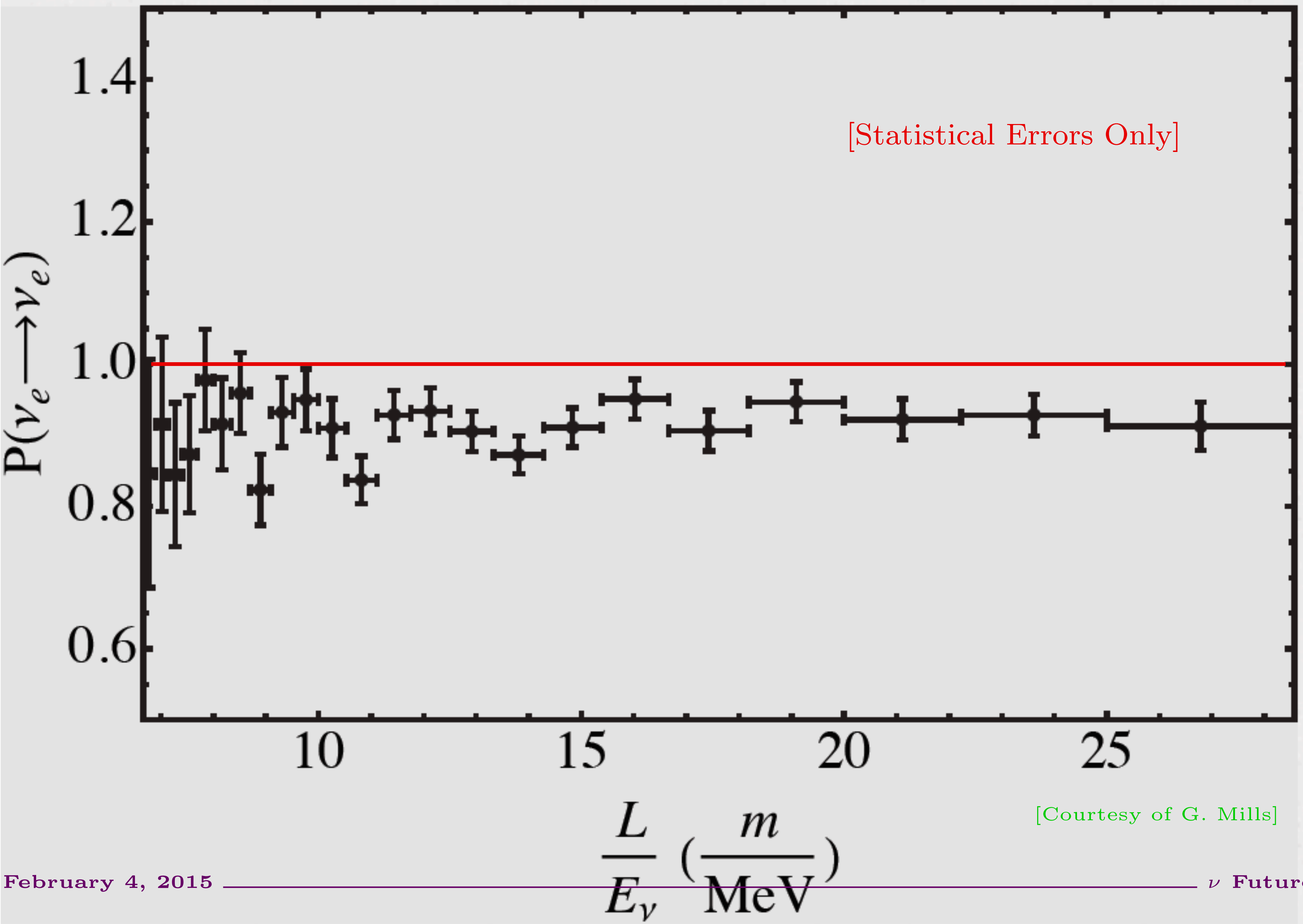
[Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439, http://www.nu-fit.org]

MiniBooNE & LSND



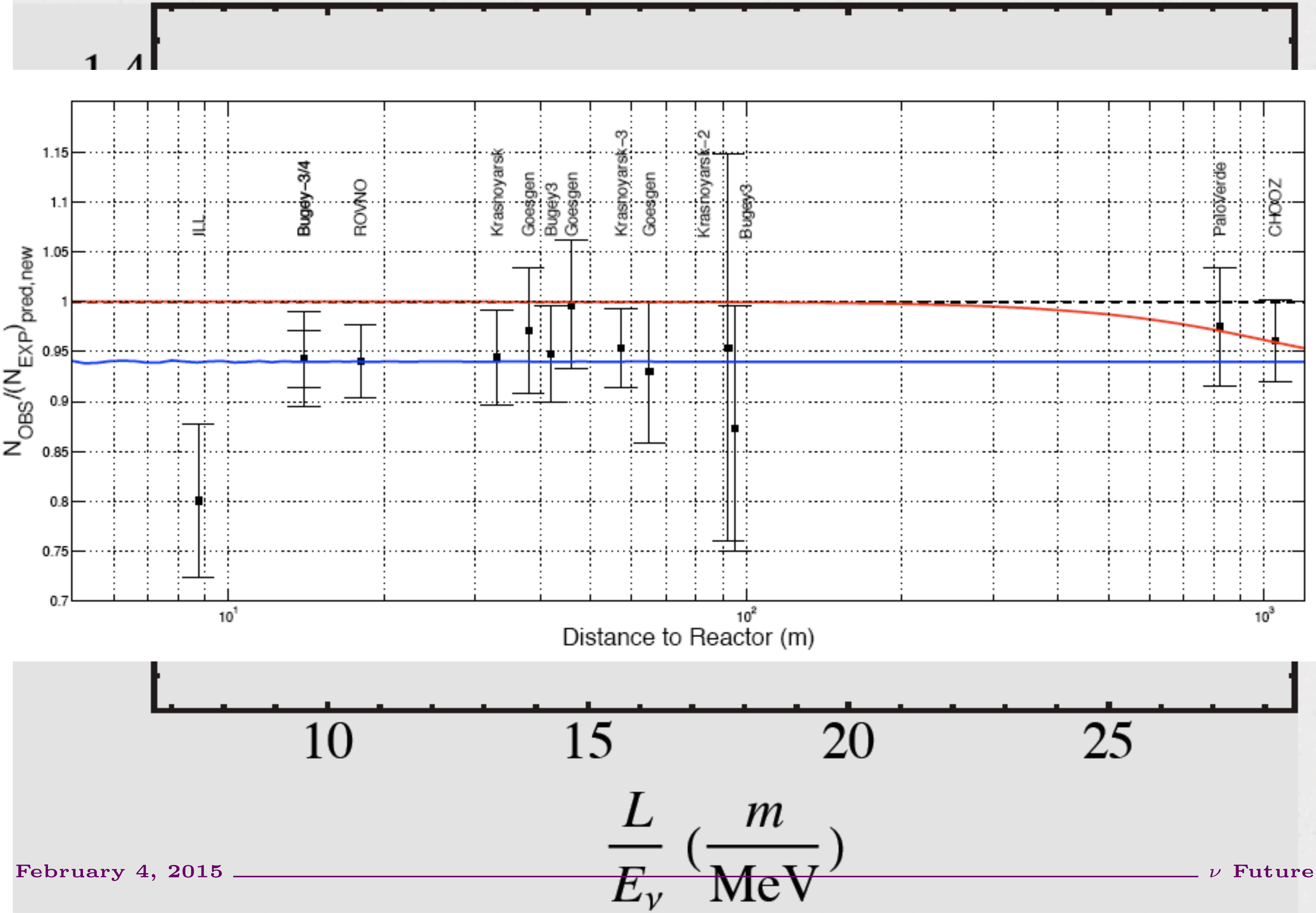
[Courtesy of G. Mills]

Bugey 40 m



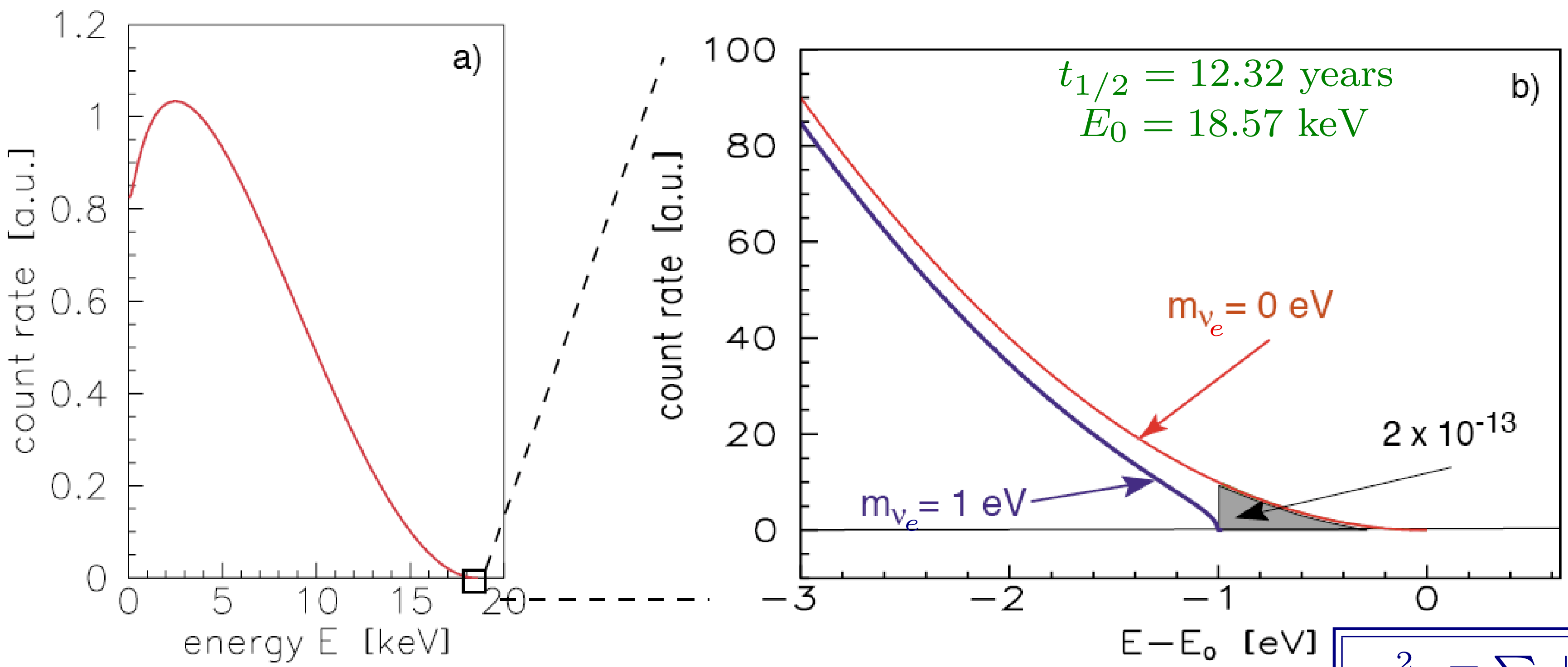
[Courtesy of G. Mills]

Bugey 40 m



ILL
Bugey-3/4
ROVNO
Krasnoyarsk
Goesgen
Bugey3
Goesgen
Krasnoyarsk-3
Goesgen
Krasnoyarsk-2
Bugey3
PaloVerde
CHOOZ
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
10^1
10^2
10^3
Distance to Reactor (m)
$N_{OBS}/(N_{EXP})_{pred,new}$
10
15
20
25
$\frac{L}{E_\nu}\ (\frac{m}{\mathrm{MeV}})$

Experiments measure the **shape** of the end-point of the spectrum, not the value of the end point. This is done by counting events as a function of a low-energy cut-off. note: LOTS of Statistics Needed!



$$\boxed{m^2_{\nu_e} \equiv \sum_i |U_{ei}|^2 m^2_i}$$

Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

NEXT GENERATION: The Karlsruhe Tritium Neutrino (KATRIN) Experiment:

(not your grandmother's table top experiment!)

$\boxed{\text{sensitivity } m^2_{\nu_e} > (0.2 \text{ eV})^2}$

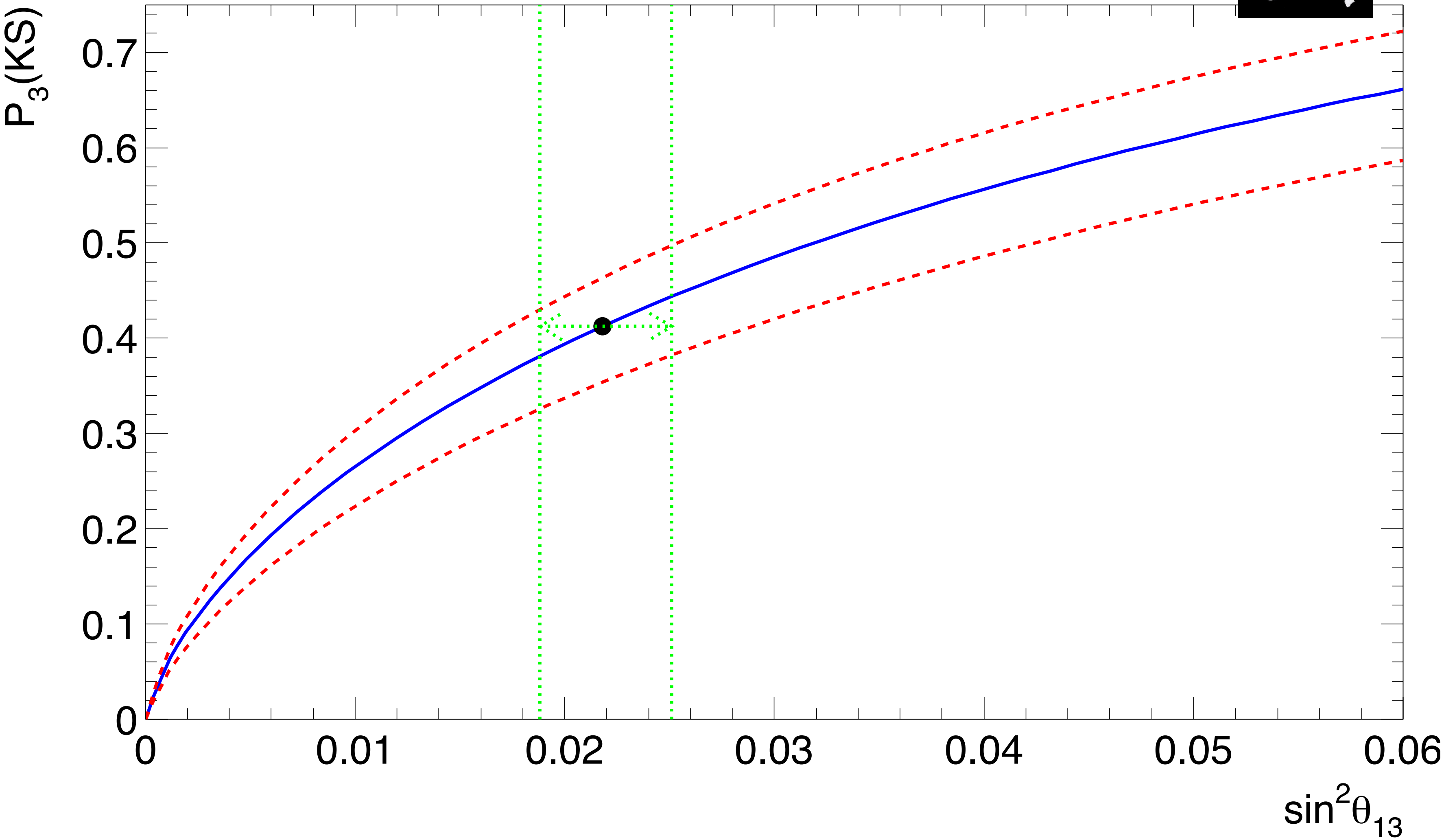
Why Don't We Know the Answer?

If neutrino masses were indeed zero, this is a nonquestion: there is no distinction between a massless Dirac and Majorana fermion.

Processes that are proportional to the Majorana nature of the neutrino vanish in the limit $m_\nu \to 0$. Since neutrinos masses are very small, the probability for these to happen is very, very small: $A \propto m_\nu/E$.

The "smoking gun" signature is the observation of LEPTON NUMBER violation. This is easy to understand: Majorana neutrinos are their own antiparticles and, therefore, cannot carry **any** quantum numbers — including lepton number.

Neutrino Mixing Anarchy: Alive and Kicking!



[AdG, Murayama, 1204.1249]